Mechatronics and Automation Technology
J.-Y. Xu (Ed.)

doi:10.3233/ATDE231123

Research on Key Technologies of Pneumatic Flexible Joints for Robots

Chao AN[a,b,1], Tianhong LUO[a], Korotkov A.N.[b], Chanjuan LONG[a,b], Guangyong WU[a,b] and Qing CHEN[a,b]

[a] *Chongqing University of Arts and Sciences, School of Intelligent Manufacturing Engineering, Chongqing, China*

[b] *Kuzbass State Technical University named after T.F. Gorbachev, Kemerovo, Russia*

Abstract. As a direct carrier of flexible motion for robots, the flexible structure characteristics of flexible joints essentially determine the flexible motion performance of robots.This article first introduces the research status of the pneumatic flexible joints at home and abroad.Then, starting from the modeling methods of pneumatic artificial muscles, the geometric models and phenomenal models were compared and analyzed. Finally, the research progress and achievements on pneumatic flexible joint control were introduced in detail. This paper has certain practical significance for the research of pneumatic flexible joints.

Keywords. Pneumatic Flexible Joints; Modeling methods; Control methods.

1. Introduction

As the direct carrier of robot's flexible motion, the flexible joint's flexible structure characteristics essentially determine the robot's flexible motion performance. Biological joints have natural and excellent motion flexibility through active/passive contraction and relaxation of joint muscles. How to imitate the physiological structure of biological joints, such as skeletal muscle groups, and learn from the active/passive flexibility generation mechanism of biological joints, to study flexible joints with excellent performance has always been a research hotspot in the robot field[1,2]. At present, scholars at home and abroad generally adopt the method of connecting flexible elements in series or flexible drive in traditional rigid joint structures to make joints have certain flexible characteristics. According to the different driving sources, flexible joints can be divided into pneumatic flexible joints, hydraulic flexible joints and electric flexible joints at this stage. According to the stiffness characteristics of different driving sources, domestic and foreign scholars have carried out systematic and in-depth optimization design for the flexible structure of flexible joints to achieve the bionic flexible characteristics of joints and meet the different motion requirements of robots.Through comparative analysis, it was found that flexible joints based on pneumatic artificial muscles are widely used in exoskeleton robots, flexible robotic

[1] Corresponding Author, Chao AN, Chongqing University of Arts and Sciences, School of Intelligent Manufacturing Engineering, Chongqing, China; Kuzbass State Technical University named after T.F. Gorbachev, Kemerovo, Russia; Emial: 904519786@qq.com.

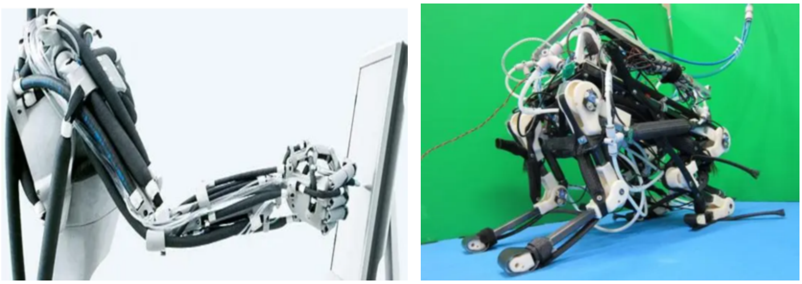
arms, and humanoid robots due to their advantages of simple structure, light weight, high output force to weight ratio, and high flexibility. They are currently a hot research topic both domestically and internationally.

2. Flexible Joint Driven by Pneumatic Artificial Muscles

Pneumatic flexible joints usually use pneumatic components such as cylinders and pneumatic artificial muscles（PAM） to drive and control joints, and use the inherent flexibility of pneumatic transmission to achieve bionic flexibility of joints. As the preferred driving element of the current pneumatic flexible joint, the pneumatic artificial muscle is mainly composed of elastic thin-walled air bags and mesh support materials. The elastic thin-walled air bags are nested inside the mesh support materials, and the two ends of the air bags are fixedly connected with the two ends of the support materials through connectors. The air pressure of the air bags is adjusted to make the air bags produce axial displacement under the restriction of the support materials to simulate the contraction and relaxation of biological muscles, Flexible driving of joints is realized[2]. The most commonly used McKibben pneumatic artificial muscle is shown in figure 1.

Figure 1. McKibben pneumatic artificial muscle

The use of multiple PAMs in parallel to simulate the tendon bone structure of organisms results in a simple, compliant, and high load to weight ratio antagonistic pneumatic flexible joint.The antagonistic pneumatic flexible joint has the advantages of simple structure, good flexibility and large load / weight ratio. Therefore, many scholars at home and abroad have derived a variety of new types of pneumatic artificial muscle joints based on the antagonistic pneumatic artificial muscle joints. Aiming at the problems of small output force and insufficient range of motion of the existing single group antagonistic pneumatic artificial muscle joints, scholars designed a cascade pneumatic artificial muscle bionic joint by using two groups of antagonistic pneumatic artificial muscle joints[3,4], and designed a 3-DOF spherical joint structure robot based on the antagonistic drive of pneumatic artificial muscle groups, The antagonistic pneumatic artificial muscle joint structure is applied to the "cheetah" robot system[5], and the bundled staggered pneumatic artificial muscle actuator designed to improve work efficiency. In order to improve the positioning accuracy, dexterity and bearing capacity of pneumatic flexible joints, scholars at home and abroad have combined antagonistic or single / multiple pneumatic artificial muscles with new mechanisms to design many new pneumatic flexible joints, including pneumatic artificial muscles with separate elastic elements and driving elements arranged by pulley structure to drive series elastic joints. By using a group of parallel pneumatic artificial muscle bundles to pull the sliding plate connecting rod mechanism, a PAM activated heavy-duty manipulator[6], a four-bar joint mechanism with two pneumatic artificial muscles and two springs in parallel and so on[7]. Aiming at the problem that it is difficult to achieve accurate control under the heavy load of bionic robot joints, some scholars, taking into account the characteristics of PAM nonlinearity, time variability and hysteresis, and inspired by the movement of biological joints under the cooperation of muscle and bone, proposed a new bionic joint structure driven by pneumatic artificial muscle and motor , It is used to improve the control accuracy and driving performance of bionic robot shoulder joint[8].The flexible joint robot based on pneumatic artificial muscles is shown in figure 2.



(a)Biomimetic robotic arm (b)Biomimetic robot dog

Figure 2. Biomimetic flexible joint robot based on pneumatic muscles

The Pneumatic flexible joints are widely used in bionic robots and rehabilitation robots due to their simple structure control, low cost, clean, pollution-free and high flexibility. However, due to the high compressibility, high viscosity and high non-linear characteristics of the gas medium itself, the existing pneumatic components generally have obvious oscillation characteristics, dynamic time delay and hysteresis characteristics, resulting in poor stiffness characteristics, frequency response characteristics and dynamic stability of pneumatic flexible joints[9]. With the rapid development of pneumatic technology, new types of pneumatic components with advanced performance are constantly emerging, which not only greatly improves the performance of pneumatic flexible joints, but also promotes the development of pneumatic flexible joints.

3. Modeling method for PAM

The PAM is the core component of the pneumatic flexible joints,studying the basic characteristics and corresponding parameter modeling methods of pneumatic artificial muscles is a prerequisite and foundation for achieving their control and application. To study the working characteristics of the pneumatic flexible joints, it is necessary to first establish the PAM's mathematical model. The most commonly used modeling methods are geometric model and phenomenal model.

3.1. Geometric Model

Based on the assumption that the pneumatic artificial muscle is an ideal cylinder, Schulte established the geometric model of the pneumatic artificial muscle; Chou et al [9,10]θ As a parameter, a static model of pneumatic artificial muscle is proposed according to the principle of energy conservation. According to the reference [11], the axial tension F of artificial muscle can be expressed as:

$$F = P'\left[\frac{3\pi D_0^{\ 2}}{4\tan\theta_0^{\ 2}}(1-\varepsilon)^2 - \frac{\pi D_0^{\ 2}}{4\sin\theta_0^{\ 2}}\right] \quad (1)$$

If the thickness t_k of the rubber tube used for artificial muscle is considered, the formula can be expressed as:

$$F = \frac{\pi D_0^{\ 2} P'}{4}(3\cos^2\theta - 1) + \pi P'\left[D_0 t_k(2\sin\theta - \frac{1}{\sin\theta}) - t_k^{\ 2}\right] \quad (2)$$

In the formula: P' is the relative air pressure inside the muscle; D_0 is the initial diameter of artificial muscle; θ_0 is the initial braiding angle of braided network management; θ is the angle between the braided wire and the long axis of the cylinder; ε is the artificial muscle contraction rate; t_k is the thickness of the rubber tube.

3.2. Phenomenal Model

In order to predict the relationship between tension, length, and velocity of pneumatic artificial muscles, inspired by the skeletal muscle phenomenon model, Colbrunn et al[9,11,12] proposed a parallel system that treats pneumatic artificial muscles as spring elements, viscous damping elements, and Coulomb friction elements, also known as the three-elements phenomenal model(as shown in figure 3). In the three-elements phenomenal model , the spring elements is used to describe the nonlinear force-length relationship, and the damping elements and Coulomb friction elements are used to describe the energy loss in the system.

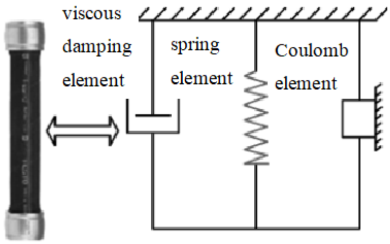


Figure 3. Three-elements phenomenal model

The disadvantage of geometric models is that the parameters can only be obtained under static conditions and are not suitable for measurement during the stretching process of pneumatic artificial muscles, which cannot describe the dynamic characteristics of pneumatic artificial muscles. The phenomenon model cannot accurately describe nonlinear phenomena such as hysteresis and creep caused by dynamic friction. Due to the strong nonlinearity of pneumatic artificial muscles, current modeling methods are not yet perfect.

4. Analysis of Motion Control Methods for Pneumatic Flexible Joints

The motion regulation of pneumatic flexible joints mainly involves compliance control of their three key output characteristics: posture, torque, and stiffness, solving the problems of low positioning accuracy, nonlinear vibration, and response lag of pneumatic flexible joints, thereby achieving safe and efficient collaborative interaction between humans and machines. Therefore, domestic and foreign scholars have adopted various control methods to study the compliance control of pneumatic flexible joints, which are divided into two categories: active compliance control and passive compliance control, mainly focusing on traditional control methods, intelligent control methods, and hybrid control methods.

In order to solve the high-precision positioning control of pneumatic flexible joints, the academic community has proposed MPI hysteresis model compensation control [3], sliding mode control [13,14], and fuzzy control [15]. In response to the problem of low motion accuracy caused by nonlinearity and hysteresis of pneumatic flexible joints, researchers have proposed various adaptive sliding film control [14] and adaptive neural network control [16,17] methods. The compliance control of pneumatic flexible joints often involves two or all of the three major output characteristics of posture, torque, and stiffness, namely achieving force-position, position-stiffness, force-stiffness, or force-position-stiffness hybrid control of pneumatic flexible joints. Scholars have designed an impedance controller with position PID inner loop based on pneumatic muscle position group and force group [18], which achieves force position hybrid control of pneumatic flexible joints through impedance control. In order to achieve position stiffness hybrid control of pneumatic flexible joints, scholars have proposed control methods such as model-based position control, fuzzy neural network compensation control. At present, research on compliance control of pneumatic flexible joints has to some extent achieved output control of posture, torque, or stiffness. However, current control methods cannot effectively solve the precise regulation of force-position-stiffness of pneumatic flexible joints.

5. Conclusion

Overall, domestic and foreign scholars have achieved many breakthrough research results in the design of pneumatic flexible joint structures, mathematical modeling, and flexible control methods. However, due to the strong nonlinearity and time-varying nature of pneumatic flexible joints, the modeling process is complex, computational complexity is large, and accuracy is insufficient, which seriously affects the control accuracy of pneumatic artificial muscles. How to explore the complex coupling relationship of pneumatic flexible joint systems, establish dynamic modeling with complete feature parameter characterization, and improve the compliance control of joint systems are urgent problems that need to be solved now.

Acknowledgements

This paper was supported by the National Nature Science Foundation of China (NO.52175215) and the Science and Technology Research Program of Chongqing Municipal Education Commission (Grant No. KJQN202201336).

References

[1] Liu X J, Yu J J, Wang G B, et al. Progress in Robot Research and Scientific Challenges [J]. China Science Foundation, 2016 (5): 425-431.
[2] Li M H, Ma YY, Zhang M L. Review on Key Technologies of bionic flexible joint [J] .Mechanical design, 2018,35 (11): 1-9.
[3] Wang B R, Zhang B, Shen G Y, et al. Modeling and fuzzy control of cascade pneumatic muscle humanoid elbow joint [J].Robot, 2017,39 (04): 474-480.
[4] Wang B R, Wang T, Guo Z W, et al. Modeling and Sliding Mode Control of a Pneumatic Muscle Quadruped Robot [J] .Robotics, 2017, 39 (05):620-626.
[5] Wang X, Li M T, Guo W, et al. Development of an antagonistic bionic joint controller for a musculoskeletal quadruped[C].2013 IEEE/RSJ International Conference on Intelligent Robots and Systems(IROS), Tokyo, 2013: 4466-4471.
[6] Ryan M. Robinson, Curt S. Kothera, Robert M. Sanner, et al. Nonlinear control of robotic manipulators driven by pneumatic artificial muscles[J]. IEEE/ASME Transactions on Mechatronics, 2016, 21(1): 55-68.
[7] Ho Pham Huy Anh, Nguyen Ngoc Son, Nguyen Thanh Nam. Adaptive evolutionary neural control of perturbed nonlinear serial PAM robot[J]. Neurocomputing, 2017, 267: 525-544.
[8] Luo T H, Li H L. Design and Dynamic Characteristics of PAM-Motor Composite Drive Biomimetic Shoulder Joint Structure [J]. Mechanical Science and Technology, 2019, 38 (02): 170-177.
[9] Xie S L, Mei J P, Liu H T. Research progress and trends in McKibben type pneumatic artificial muscles [J]. computer integrated manufacturing system, 2018, 24 (05): 1064-1080.
[10] CHOU C P, HANNAFORD B. Measurement and modeling of McKibben pneumatic artificial muscles[J].IEEE Transactions on Robotics and Automation, 1996,12(1) :90-102.
[11] Hao l N. Technologies of Artificial Muscle and Bionic Actuation[M]. China: Science and Technology Press.
[12] COLBRUNN R W. Design and control of a robotic leg with braided pneumatic actuators[D]. Cleveland, Ohio, USA:CaseWestern Reserve University , 2000.
[13] Hiroki Tomori, Yuichiro Midorikawa, Taro Nakamura. Construction of a nonlinear dynamic characteristic model of pneumatic artificial rubber muscle manipulator using the magnetorheological (MR) brake[J]. Journal of Intelligent Material Systems and Structures, 2012, 23(9): 1011-1018.
[14] Ryan M. Robinson, Curt S. Kothera, Robert M. Sanner, et al. Nonlinear control of robot manipulators driven by pneumatic artificial muscles[J]. IEEE/ASME Transactions on Mechatronics, 2016, 21(1): 55-68.
[15] Wang B R, Lu H, Jin M T, et al. Pneumatic Muscle Elbow Joint MPI Hysteresis Model and Compensation Control [J]. Journal of Agricultural Machinery, 2019, 50 (06): 412-418
[16] Ho Pham Huy Anh, Nguyen Ngoc Son, Nguyen Thanh Nam. Adaptive evolutionary neural control of perturbed nonlinear serial PAM robot[J]. Neurocomputing, 2017, 267: 525-544.
[17] Nguyen Ngoc Son, Cao Van Kien, Ho Pham Huy Anh. A novel adaptive feed-forward-PID controller of a SCARA parallel robot using pneumatic artificial muscle actuator based on neural network and modified differential evolution algorithm[J]. Robotics and Autonomous Systems, 2017, 96: 1-30.
[18] Liu Y, Wang T, Fan W. Structure and Impedance Control of Ball Joint Robot Driven by Pneumatic Muscle Group [J]. Journal of Mechanical Engineering, 2013, 49 (15): 28-33.